Stochastic Matched Field Processing and Array Processing in Snapshot-Limited Environments

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LONG-TERM GOALS

The long term goals are to develop adaptive matched field and planar array processing methods which are robust to environmental mismatch, *e.g.* internal waves, sea surface and bottom roughness as well as stochastic mismatch caused by nonstationary fields leading to snapshot deficiencies for adaptive processing.

OBJECTIVES

There are two objectives. i) Matched field field methods exploit the vertical propagation structure of signals to estimate range and depth, so perturbations in this structure lead to smearing and often a complete loss focusing. This is caused by mismatch between the replica vector and the actual Green's function vector in the medium. Our first objective is to mitigate these effects by using a more robust approach which we have labeled as stochastic matched field processing. ii) All adaptive array processing must address the problem of snapshot limitations if the ambient environment is nonstationary. There is a tradeoff here in the two approaches to the processing. If one use nonparametric methods such as those based on sample covariances, then these covariance matrices estimates must be stable and this requires a large number of snapshots. Alternatively, one can use parametric methods which include the propagation constraints which should supplement for some of the knowledge of the covariance structure. With these methods one is lead to nonlinear algorithms and the possibility of signal mismatch.

APPROACH

The approach for stochastic matched field processing is to generalize the models used for representing the target and noise processes. In all the MFP algorithms used to date the signal replica has had one degree of freedom, *i.e.* it could be represented as the product of a single vector and a random variable. With complicated and random propagation effects a more robust model is to represent the signal with more than one degree of freedom. This has often been done in time series analysis when the signal bandwidth exceeds the the reciprocal of its duration. This has two advantages. First, it gathers more of the signal energy and recovers some to signal degradation due to mismatch. Second, if one use parametric nulling of noise, it provides a wider sector for the interference instead of requiring an exact, and probably inaccurate, cancellation by single degree of freedom nulling.

Our approach to limited snapshot problem is to represent the signal as a superposition of signals which spans the entire propagating space to within a fraction of the nominal beamwidth of the array plus additive white noise. Many authors have done this is time series analysis. One can then derive a stationarity condition for the maximum likelihood estimate for the mean square level of each of the spanning conditions and the white noise level. This has a very intuitive interpretation with respect to minimum variance distortionless response beamforming (MVDR). If one has a representation of the field according to the above superposition, one can easily find the MVDR beamformer and its mean square response by their well known formulae. The stationarity condition requires that the response of the MVDR beamformer to the sample covariance must be equal to the MVDR mean square response. This suggests an iterative approach to the beamforming which incorporates both the propagation physics, so it can be generalized for MFP methods, and the nominal resolution of the array, so one avoids superdirective responses. One can also generalize this to include moving targets by generalizing the source models, but this comes at the expense of requiring more parameters to represent the velocities.

WORK COMPLETED

The Stochastic Matched Field Processing (SMFP) approach was analyzed by Peter Daly as his doctoral dissertation. He concentrated on the target detection problem using data from the Santa Barbara Channel Experiment (SBCX). This approach was able to detect signals at longer ranges on the SBCX vertical arrays when compared to other algorithms. We are continuing work on the nulling aspect of the SMFP, which is where its greatest potential may be for robust nulling with *a priori* information about interfering sources.   In addition, we are developing Cramer-Rao bounds for stochastic source models. Some of this work has also found use in the RPS program.

The work for using limited snaqpshots has had some successes and some problems. Essentially, we are using a generalized likelihood ratio method. We have been able to demonstrate improvement over the MVDR approaches for both ensemble and sample covariances situations with limited rank for signals which are marginally detectable; however, we have had problems with convergence for the algorithm. This seems to be coupled to the estimate of the white noise level wherein if falls below its true value, the results tend to diverge even with ensemble covariance. Estimating the white noise level has been a problem in other algorithms since this requires the propagating signals to span the underrepresented component which does lead to stability problems. We also continue to work on incorporating moving sources with a manageable number of parameters.

RESULTS

Stochastic Matched Field Processing: The SMFP approach was applied to the SBCX data and some sample results are indicated in Figures 1 and 2. The experimental context is a single 30 sensor vertical array in the Santa Barbara Channel which has a downward refracting profile. The source to receiver range is approximately 15 kms. The source is roughly stationary, so there is no issue regarding adequate snapshot support. In Figure 1 the data were processed using the standard single degree of freedom replica, or the so called conventional method. The source is located at the intersection of the dotted lines; however, the peak is far away and there is only a vague hint of it being in the correct location.

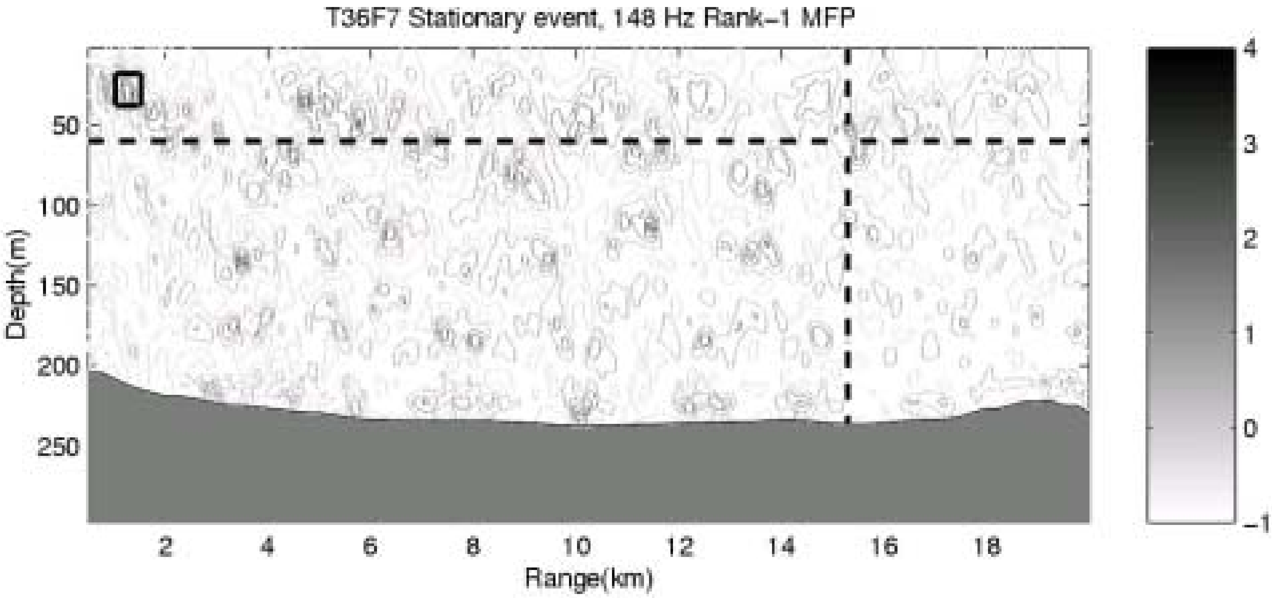

Figure 1
Range – Depth Ambiguity Diagram for the Acoustic Explorer Source at 15 km in the Santa Barbara Channel Experiment with Conventional MF processing

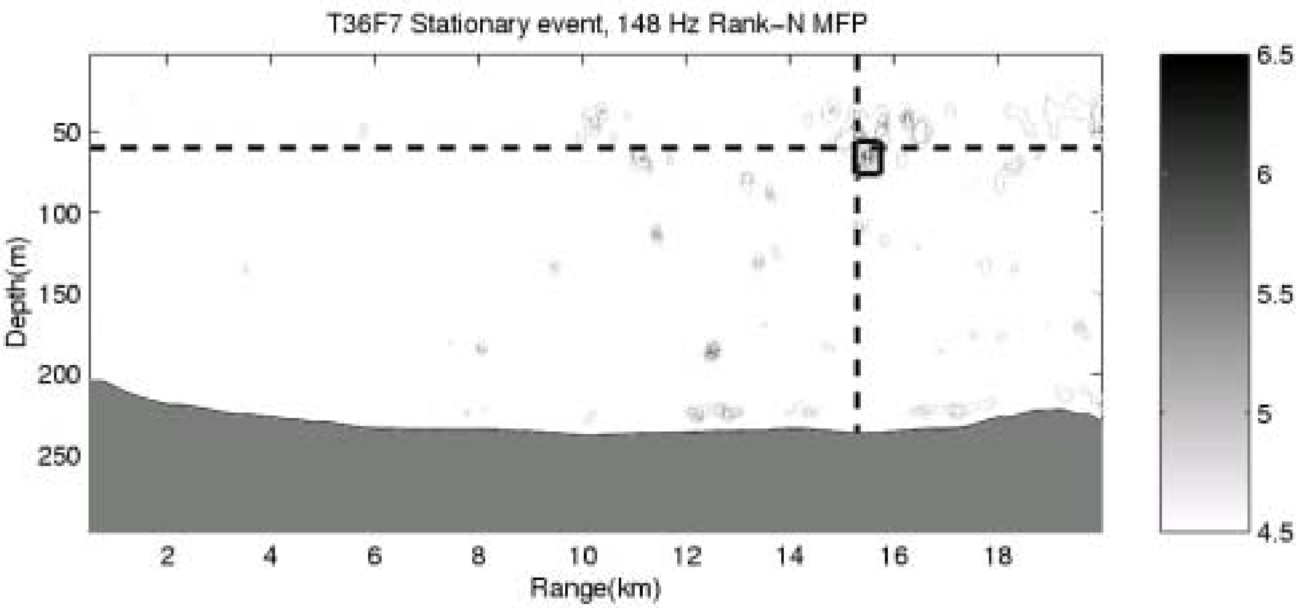

Figure 2
Range – Depth Ambiguity Diagram for the Acoustic Explorer Source at 15 km in the Santa Barbara Channel Experiment with Stochastic MF processing

In Figure 2 we have used SMFP with N = 30 degrees of freedom included in the processing. Here we can see that the peak is quite close to actual location known from the GPS tracking and the sidelobes have been attenuated somewhat (For an exact comparison the dynamic range of the figures should be the same).

Finite Snapshot Processing: We use as an example a 30 element circular array with a radius of 1.5 wavelengths. The ambient noise has three components: white noise, isotropic noise and three discrete sources with levels of 12, 9 and 6 dB. (Recall that isotropic noise has a "bowl" shaped 2D wavenumber distribution. The comparisons below indicate the performance of the MVDR and the generalized likelihood ratio method with both ensemble covariance as an algorithm asymptotic baseline and with sample covariances with N=30.

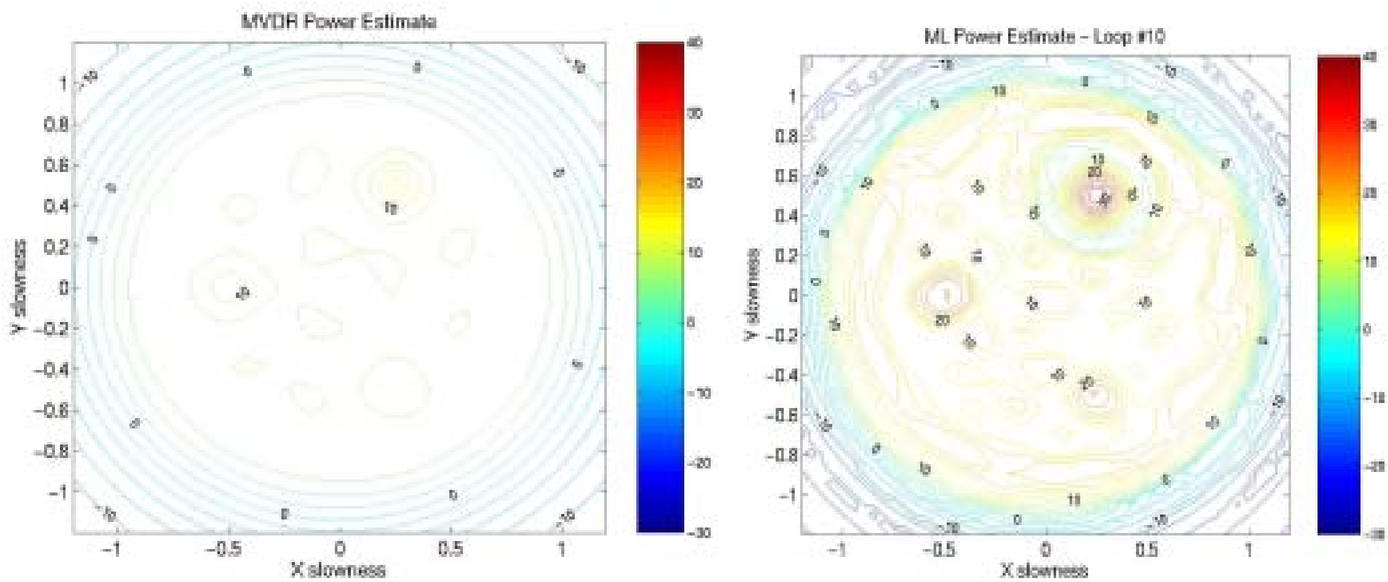

Figure 3
Comparison of MVDR and generalized likelihood (GL) processing on an ensemble covariance. Note that the GL processing identifies the peaks with significantly higher level as well as the "bowl" shaped structure of the 2D isotropic

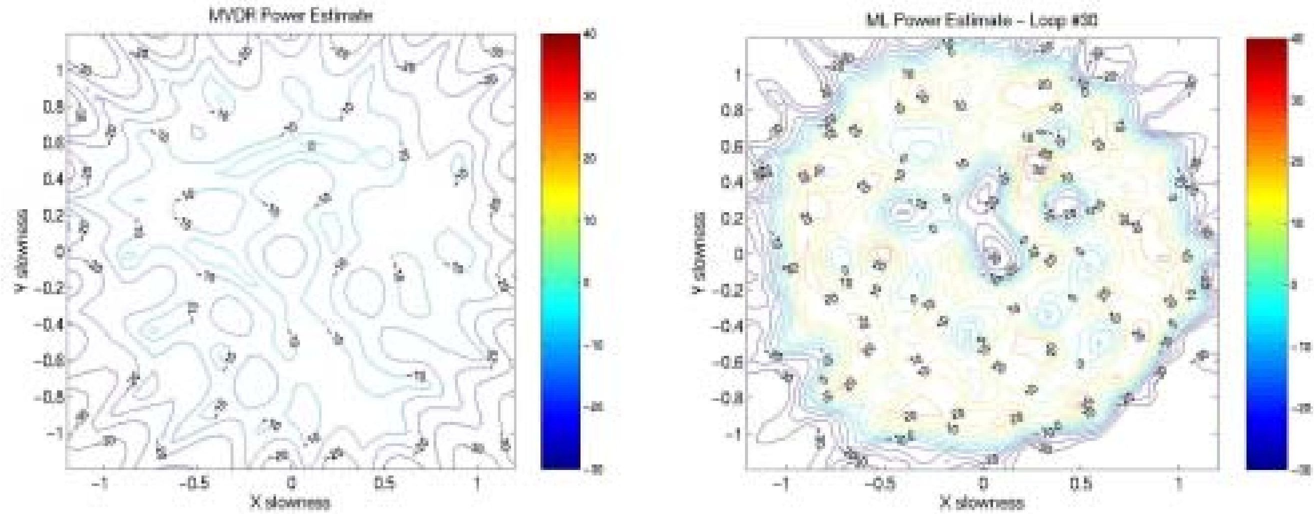

Figure 4
Comparison of MVDZFR and GL processing on a sample covariance (N=30) covariance. Note that the MVDR does not resolve any of the discrete sources whereas the GL indicates the tow kargest as well as the bowl shaped structure of the isotropic noise.

One can observe that the generalized likelihood (GL) method performs better with both the ensemble and the sample covariances. The discrete sources are better detected and resolved as well as the "bowl" shaped structure of the 2D isotropic noise. There are many features of the GL processing which remain unknown. First, it requires a minimization of a function with several peaks. We have tried a number of algorithms including simulated annealing to achieve this global optimization. Second, we do not understand the trade of between the density of the support space and the number of snapshots used.

IMPACT/TRANSITIONS

Both of these issues have significant impact upon the performance of USN sonar arrays in the near term. MFP has had been demonstrated to work successfully in several carefully controlled experiments, but there is but one application where it is used operationally. The key issue is that it exploits the physics of the propagation, but needs to be robust the errors in the modeling. Similarly, snapshot deficiency has been a problem for all adaptive processing with nonstationary environments such as those created by moving ships. An effective solution would have an immediate transition to operational systems.

RELATED PROJECTS

The concepts for much of this work were formulated as part of the ONR Working Group for the Acoustic Observatory (now the Shallow Water Acoustic Testbed. (SWAT)). Other related projects the Robust Passive Sonar (RPS), the ONR North Pacific Acoustic Laboratory and some classified programs. These issues are also routinely raised as part of the discussions of Submarine Superiority Technical Advisory Group (SSTAG).

PUBLICATIONS

Baggeroer, A. B. and Cox, H., "Passive Sonar Limits Upon Nulling Multiple Moving Ships with Large Aperture Arrays, 33rd *Proceedings of the 1999 Asilomar Conference on Signals, Systems and Computers,* IEEE Press, New York, (1999), not reported in 2000)

Baggeroer, A.B. and Daly, "Stochastic Matched Field Array Processing for Detection and Nulling in Uncertain Ocean Environments, 34th *IEEE Conference Proceedings of the 2000 Asilomar Conference on Signals, Systems and Computers,* pp 662-667, IEEE Press, New York, (2000)